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Reports
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ENVIRONMENTAL FACTORS AFFECTING NATURAL SUCCESSION ON COAL MINE SPOILS

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INTRODUCTION

Strip-mining for coal and other mineral resources in the southwestern U.S. has produced problems in reclamation entirely different from those encountered in regions of higher or more effective precipitation. While concern over the reclamation of western coal fields is still a relatively recent phenomenon, the general realization that differences in problems and remedies do exist is even more recent. As a result, only a small fraction of the literature dealing with the reclamation of devastated lands addresses itself to the problems of revegetation in arid and semi-arid regions. Of this relatively small amount of work done so far, almost all has involved to at least some degree the testing and comparing of agronomic techniques and manipulations in an attempt to test the suitability of and to promote the establishment of vegetation on coal-mine spoils. It was the intent of this study to look at the essentially random assortment of environmental factors left after the mining process and to determine qualitatively, as well as quantitatively, which of those factors or combination of factors are more likely to lead to the successful germination and establishment of invading plant species. A second objective was to determine within a number of parameters what changes in the spoil material are occurring as a result of plant establishment.

Most of the research found in the literature has been conducted by either government agencies or various universities.

Studies into the acceptability of coal mine spoils as a growth medium have been conducted on spoils from a number of locations (Aldon and Springfield 1973, 1975; Yamamoto 1975). The general conclusions are that spoil material in itself is a fairly acceptable medium of growth. The factor of greatest importance is the unfavorable water relations typical of the arid West. Consequently, a large proportion of the work being conducted centers on the development of different treatments and surface manipulations intended to increase the amount of moisture available for plant growth. Hodder (1973) has directed much effort in this regard. He has successfully used "deep chiseling", "gouging", and the creation of "dozer basins" in an effort to impede water flow, conserve runoff, and in general trap moisture in order to make more available for revegetation. Jacoby (1969) studied the use of snow fences, jute net, and straw mulch on Wyoming coal spoils to accomplish the same thing. He found that a combination of jute netting and mulch gave the best results. Evidence also suggested that older spoil material was more suitable for planting. Work has also been done in the *a priori* classification of potentially stripped land based on the degree of difficulty in rehabilitation (Packer 1974).

This study was conducted at Pittsburgh and Midway's McKinley Coal Mine located approximately 18 miles northwest of Gallup, New Mexico. Large scale strip-mining has occurred there since 1961, thus affording some spoil banks up to 14 years of age. The elevation of the area studied is approximately 6700 feet.

The average annual precipitation at the mine is 12.61 inches with recorded extremes of 5.32 and 23.73 inches. The months of July, August, and September are the wettest, averaging 2.06, 2.26, and 1.25 inches respectively. Monthly precipitation amounts for October through March average 0.90 in. while April, May, and June average 0.66, 0.57, and 0.51 inches respectively. Summer precipitation occurs as afternoon thundershowers that rarely last longer than one-half hour. Winter precipitation is generally gentler than that of the summer, the storms normally lasting longer and being more widespread in nature. Approximately 70 percent of winter moisture falls as snow, but accumulations of more than one foot are rare (USDA 1975).

Annual average temperature at the mine from 1963-1972 was 51^{o}F. July was the hottest month with an average daily maximum of 90^{o}F and the months of December and January were the coldest with average daily minimum and maximum temperatures of 18^{o}F and 47^{o}F respectively.

Materials outcropping or subcropping in the McKinley Mine site are mainly sandstones and shales of the Gibson and Cleary members of the Menefee and Crevasse Canyon formations. Most of the surface area is covered by residual and alluvial soil materials. Outcropping sandstone occurs particularly on the ridges. Shales underlie surface soils beneath the valley slopes and low-lying areas. In the formations in which the mining takes place, the stratigraphy is complicated. Coal occurs in up to five mineable seams and in numerous thin seams and stringers. The overburden consists of interbedded lenses of sandstone and shale with individual strata ranging in thickness from 0.1 to 15 feet. It is estimated that shale constitutes 56.7 percent of the overburden and sandstone 43.3 percent. The shale is a very weak rock with most of the properties of a soil. It consists predominantly of clay-sized particles and exhibits significant volume changes with changes in moisture content, suggesting that it contains a considerable proportion of montmorillonite. The sandstone consists mainly of medium to fine grained quartz in an argillaceous matrix. It ranges from weak to medium strong. Rocks with a composition and texture between those of sandstone and shale are also quite common (USDA 1975).

The vegetation at the site prior to mining was dominated by two principal plant communities: pinyon-juniper and sagebrush. Species composition and productivity of both communities had been strongly influenced by past overgrazing.

The object of this study was not to document the types and percentages of plant species that had slowly become established on the spoils. This had already been done by Warren Wagner (1975). Rather, it was to see if the relatively small amount of invasion of plants onto the spoils had already started the natural process of succession and what original factors had existed to permit this invasion. The purpose then, was to translate these findings into a program that would merely accelerate success and at less expense than with the more conventional methods presently employed.

Appreciation is expressed to Earl Aldon and the Rocky Mountain Forest and Range Experiment Station for the financial support of Cooperative Agreement No. 16-552-CA which made the research possible. Credit is also extended to Paula Woodbridge for her exacting laboratory analyses.

METHODS

A number of sites mined in the 1960's were studied. Some of the sites had been left after mining in typically steep, sharp-angled spoil banks. Others had been contoured into a rolling topography following mining.

In the first year of the study (summer 1975) mostly visual observations were made. However, temperature and floristic data were also collected as were spoil samples from under and near established plants. These spoil samples were taken at the 0-5 cm and 12-17 cm levels. One was taken from underneath the plant (A), the second from where the spoil was bare and appeared to be unfavorable to plant establishment (B), and the third from bare spoil that appeared to be similar to site A, less vegetation (C). It was later decided that the differentiation between samples B and C was too subjective and open to error.

During the following year, the 1964-66 mine spoils were studied more intensively. Assuming that the mining process had ended in 1966, these spoils had been free of further disturbance for 10 years.

One site on these spoils was heavily populated by mature four-wing saltbush (Atriplex canescens). This area had been only superficially graded following mining activities and was located at the north end of the spoils in question. From here, sets of spoil samples were collected. Each set was taken from the area immediately surrounding a mature four-wing saltbush. All the plants were of approximately equal size (average 1.63 m in diameter; 1.1 m high). Samples were taken at three different depths and at three different horizontal zones. The depths were located at 0-5 cm, 12-17 cm, and 32-37 cm. Zones sampled were: at the trunk of the plant (C), at the outer edge of the plant canopy (P), and at one meter north of the canopy edge (M). Thus, nine samples of approximately 400 g each were taken from beneath each sampled plant. Because of expense condiderations, only six sets of nine were completely analyzed. From the data obtained, it appears that this number was adequate in most cases to provide some idea of what was occurring in terms of ion and moisture movement below the shrub canopy. The "M" samples were meant to provide a control value as they were taken from unvegetated areas.

Elements studied in the described samples were calcium, magnesium, sodium, and potassium. These elements were chosen because of their importance to successful plant establishment, their value as indicators of salt relations in the spoil material, and also because of their relative ease of determination. Analysis of two other elements, nitrogen and phosphorus, would have been desirable. Nitrogen was finally omitted due to problems with the Kjeldahl digestion of the spoil material. Phosphorus was dropped because of the lack of a reliable test for the element.

Values obtained for the four elements tested indicate concentrations available to the plant as represented by ammonium acetate extraction rather than total amounts present. Values are given as milliequivalents per 100 grams of soil. Analytical procedures are listed in the appendix.

Other analyses of the above samples included electrical conductivity, field and saturated paste moisture percentages, pH, cation-exchange capacity (CEC), and spoil texture. Organic matter determinations would have been valuable; however, the presence of variable amounts of coal in most samples precluded the possibility of any useful data.

Field moisture determinations were made upon arrival at the lab. Saturated pastes were also made of each sample and the moisture saturation percentage was then determined for these also. The ratio of field moisture percentage to saturated moisture percentage was used as a common measure of the amount of moisture being held by each sample.

Due to the many and varied types of terrain found on the spoil banks, sites for vegetational analyses were stratified in order to obtain more homogeneous samples. Areas studied were divided into 1) "rolling plains", 2) deep drainages, 3) four-wing saltbush stands, and 4) Russian olive stands. Species composition and foliar coverage were estimated using a rectangular quadrat 0.5 x 1.0 m along a 180-meter transect. The transect was sampled every 3 meters and foliage cover was estimated as a percentage of total foliage cover.

Minimum and maximum soil temperatures on north and south exposures, both bare and covered, were recorded.

Registering thermometers were placed just below the spoil surface on adjacent north and south slopes. The covered sites were those beneath the canopies of four-wing saltbush. Corresponding air, bare spoil, and covered spoil temperatures were also taken with pocket thermometers.

In addition to the above quantitative analyses, much time was spent traversing and observing the spoil areas trying to get a feel for what natural processes were occurring.

RESULTS AND DISCUSSION

Elemental and other chemical and physical data were subjected to two-way analyses of variance (depth as one factor; zone as the other factor). Data presented in tables and graphs represent average values based on six samples. Subscripts on zone designation (C, P, or M) represent depths at which samples were taken (Table 1).

Elemental Analyses

Calcium

Analysis of the calcium data showed a significant increase ($P<.01$) existed from the 5 cm to the 35 cm levels at any zone. However, since there was no corresponding significant difference between zones C and P and M, no movement of calcium by the plant is indicated; only a natural leaching downward in the spoil is shown.

Magnesium

For the existing sample size, there was no apparent addition or subtraction of magnesium in the soil due to plant establishment. A larger sample number might, however, show a significant accumulation of the element beneath the plant canopy.

Sodium

Sodium concentrations differed significantly ($P<.01$) between the 15 cm and 35 cm depths and very significantly ($P<.001$) between the 5 cm and 35 cm depths for any zone, being greatest in the deepest level. Unlike calcium, there

Table 1. Mean values for various spoil characteristics of samples obtained at three different depths in three different zones around *Atriplex canescens*

Zone & Depth	Meq/100g Ca	Mg	Na	K	pH	Ec[1]	ESP[2]	Field[3] Moisture Percent
C 5	19.31	8.02	0.14	4.21	8.60	2.24	0.87	13.0
15	20.62	5.74	0.32	1.21	8.36	1.37	3.10	23.9
35	24.53	6.50	1.27	0.94	8.16	2.67	10.75	24.5
P 5	19.61	6.32	0.61	3.13	8.55	2.51	4.91	11.1
15	25.13	5.66	1.04	0.73	8.04	2.64	9.57	22.5
35	34.81	7.67	2.16	0.58	8.09	4.25	16.68	24.1
M 5	16.82	6.52	0.99	1.40	8.32	3.10	9.21	7.04
15	26.61	6.31	1.70	0.74	8.01	3.61	13.97	20.5
35	30.88	8.12	3.70	0.71	8.20	5.42	22.92	24.5

[1] Electrical conductivity expressed as mmhos/cm at 25°C

[2] Exchangeable sodium percentage is percentage of the cation-exchange capacity occupied by the sodium cation

[3] Ratio of the field moisture percentage to the saturated paste moisture percentage. Values based on five samples each; one was left out because of recent rain

was a significant difference ($P<.001$) between zones C and M at any of the three depths. One might initially assume that the plant is picking up the Na^+ and is thus depleting the root zone of the ion since halophytes often exhibit a clear preference for sodium over potassium (Waisel, p. 125, 1972). However, the leaf litter from the plant would be high in sodium and would constantly replenish the sodium level at the spoil surface; a situation not reflected by the data.

From visual as well as gravimetric determinations it became apparent that moisture from summer thunderstorms was being funneled by stemflow to the main stems resulting in large concentrations of moisture infiltrating the soil along the plant tap root. This penetration and leaching explain the lowered concentration of Na^+ within the plant's sphere of influence since, unlike the calcium and magnesium salts present, the sodium salts are very water soluble. A natural consequence of this higher moisture-lower Na^+ environment would be an increase in less salt-tolerant grass and forb species underneath the shrub. That is precisely the case (Figure 1).

Potassium

The change in distribution of potassium as a result of plant establishment was the most marked of the four elements tested. Not only were values as a function of either depth or zone highly significant ($P<.01$) but there was also a very highly significant interaction ($P<.001$) between depth and zone. Concentrations were greatest in surface soils and directly under the shrub (Figure 2). There are a number of

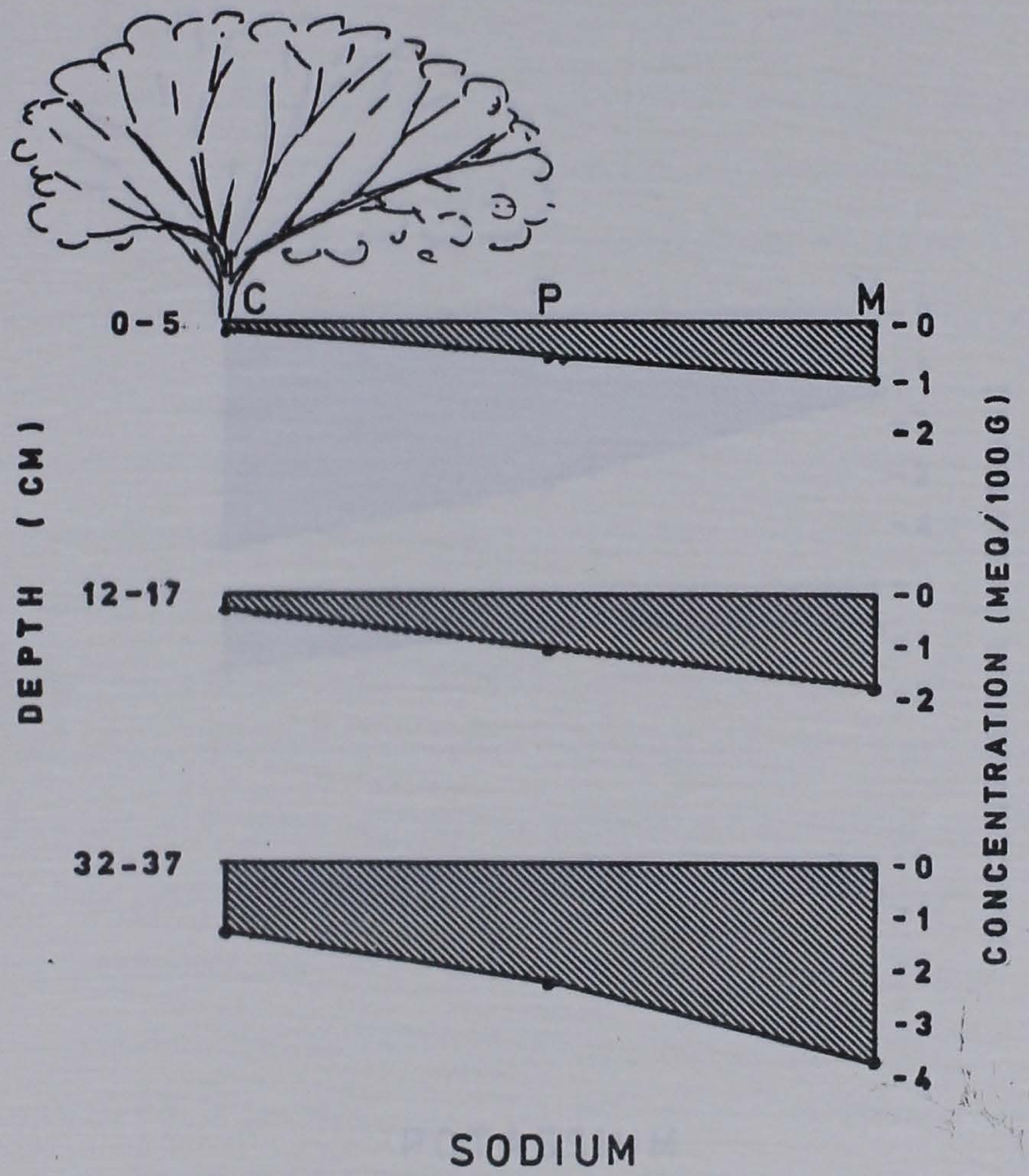


Figure 1. The ecological reaction of a single four-wing saltbush plant on sodium concentration as related to zones C, P, and M (base, periphery, and beyond the canopy) and three depths.

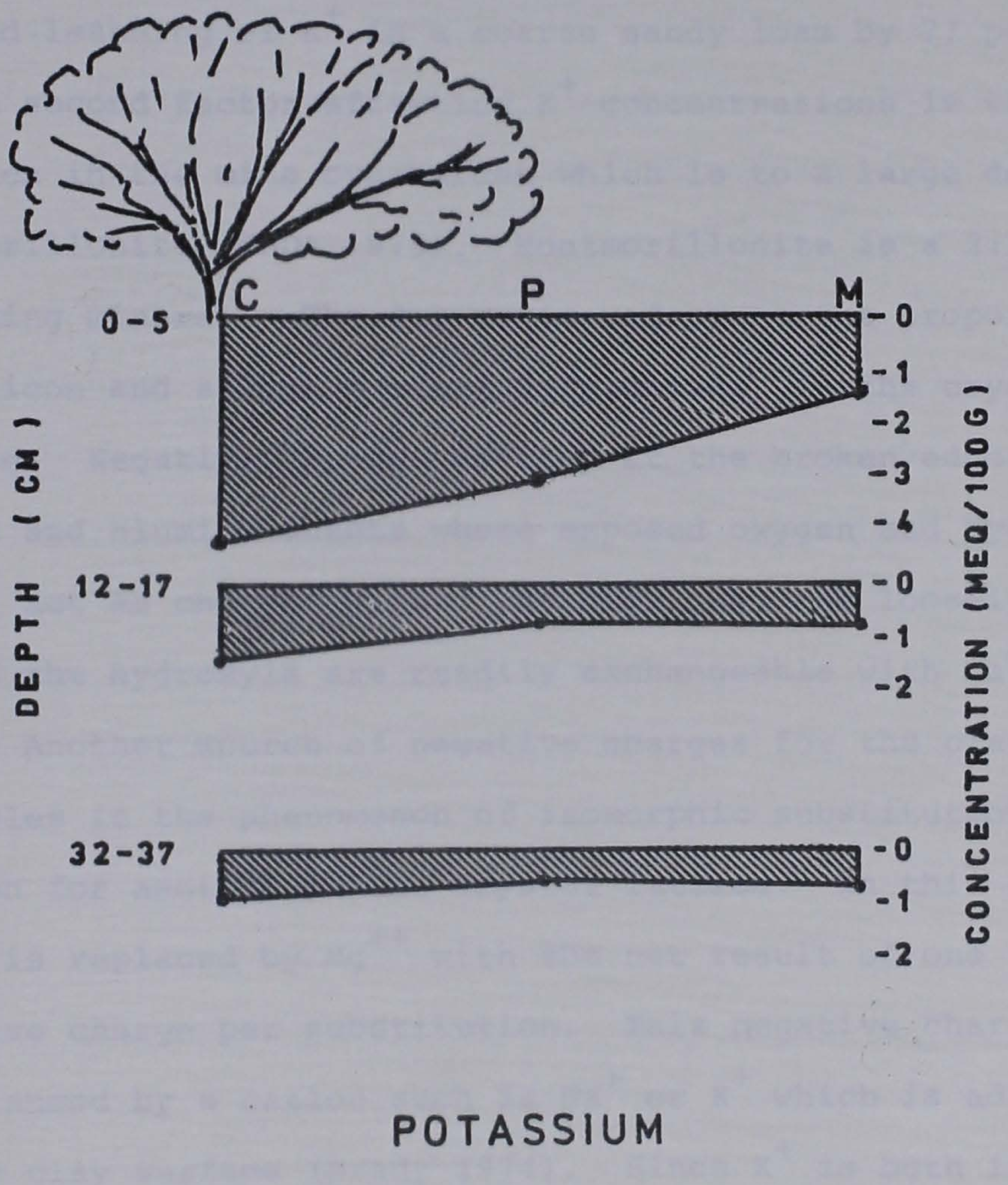


Figure 2. The ecological reaction of a single four-wing saltbush plant on pottasium concentration as related to zones C, P, and M (base, periphery, and beyond the canopy) and three depths.

possible explanations for the accumulation of potassium under the shrubs. The accumulation of K^+ under the plant might be due in part to the action of the plant in transporting K^+ to the surface (Black 1968). There are several possible reasons to prevent the K^+ from being leached downward. In a study by Baver (1943) an increase in pH from 4.83 to 7.03 reduced leaching of K^+ in a coarse sandy loam by 77 percent.

A second factor affecting K^+ concentrations is the clay fraction in the mine overburden which is to a large degree montmorillonite (USDA 1975). Montmorillonite is a 2:1 type expanding mineral. The 2:1 ratio refers to the proportion of silicon and aluminum atoms respectively in the crystal lattice. Negative charges develop at the broken edges of the silica and alumina sheets where exposed oxygen and hydroxyl groups act as charged sites. At high pHs, the loosely held H^+s of the hydroxyls are readily exchangeable with Ca^{++} and Mg^{++}. Another source of negative charges for the clay particles is the phenomenon of isomorphic substitution of one ion for another in the crystal lattice. In this case, Al^{+++} is replaced by Mg^{++} with the net result of one negative charge per substitution. This negative charge must be balanced by a cation such as Na^+ or K^+ which is adsorbed by the clay surface (Brady 1974). Since K^+ is both in greater supply, even in the "M" zone, than Na^+, and since K^+ is usually ahead of Na^+ on most replacement sequences, the former is more likely to be adsorbed onto the clay surface. This would tend to hold K^+ near the surface despite the leaching process.

A third factor affecting K^+ is the presence of 2:1 clays in which K^+, as well as NH_4^+, ions fit in between the silica sheets of adjoining crystal units and become an integral part of the crystal. This form of K^+ is in equilibrium with available forms and consequently acts as a slow release reservoir (Brady 1974). This too would act to prevent the downward leaching of potassium in contrast to sodium.

The extraction process employed in the analyses involved the use of NH_4OAc. Since both NH_4^+ and K^+ can be trapped by the crystals, it is very likely that the NH_4^+ used in the extraction replaced by mass action most of the K^+ ions held in the crystal in an otherwise less than readily available state. This situation may then be responsible for some positive bais in the potassium values obtained in that some of the K^+ extracted was not in a readily available form. However, the relative values are still of use in showing zonal accumulation.

Because of this entrapment of K^+ and NH_4^+ by the clay's crystal structure, normal crystal lattice expansion is prevented and CEC is reduced (Brady 1974). Since the conditions existing in the study area would more than likely preclude the presence of much, if any, NH_4^+ ions, K^+ is probably of major importance in this regard. A possible ramification of the prevention of crystal expansion is the improved percolation properties of the spoil material immediately below the shrub canopy.

A number of other benefits might possibly accrue if K^+ concentrations continued to build. Two which would have importance at the mine include increased plant growth and resistance to low temperatures. Although potassium at one time appeared to have a beneficial effect on the water economy of plants, it appears now that that is only an indirect consequence of greater growth induced by potassium fertilization (Black 1968). Whatever the reason, the effect would be helpful. Studies with potassium fertilized and deficient plants show that plants supplied with adequate potassium are more resistant to frost, thereby extending their growing season (Boysen 1933; Shickluna et al. 1965; Wang et al. 1953). The effect on natural succession is of course a greater production of biomass and consequently more ecological reaction (a change in the environment produced by an organism).

Other Chemical Analyses

pH

Statistical analysis of the pH data showed no significant differences between values obtained from the different zones at any particular depth. It did show highly significant differences between depths. This, however, occurred in all zones, including the control (M). Therefore, although there appears to be a trend toward higher pH values under the plant, statistically, any decrease with depth must be attributed to a process unaffected by plant growth. Regardless of the above, pH does not appear to be a problem in regard to plant establishment. An advantage to the existing pH of approximately 8 is the favorable environment it affords the nitrogen-fixing bacterium *Azotobacter* which also does very well in saline and sodic soils (Waisel 1972).

Electrical conductivity and exchangeable sodium percentage

Although there were a few high values obtained, (range = 0.69 to 10.13 mmhos/cm) the average Ec values indicate fairly low amounts of soluble salts. The high values occurred at the 35 cm level. Electrical conductivity varied significantly only between the C and M zones where concentrations were significantly different for the 5 cm and 15 cm levels compared to the 35 cm levels.

The exchangeable sodium percentage (ESP), which is the percentage of sodium saturation of the cation-exchange capacity, provided an index of certain nutritional conditions and of unfavorable physical properties that either exist in the soil or may develop upon removal of the salts (Black 1968). In addition, exchangeable sodium percentage is the second criterion employed along with Ec in the classification of salt-affected soils. Thus ESP was calculated using the empirical equation developed by the U. S. Salinity Lab Staff (1954):

$$\text{ESP} = \frac{(1.47)\ (\text{SAR}) - 1.26}{(.0147)\ (\text{SAR}) + 0.99}$$

Using the above classification, only two sites had values other than normal. These, P-35 and M-35, are saline-sodic.

The effect of plant establishment appears to be that of reducing the ESP in the spoil within the zone of shrub influence. Again, potassium, more than any other observed factor, appears to be responsible for this reduction in ESP. The fact that there is a K^+ buildup, that there is little change in pH, and that there is only a small significant change in conductivity (apparently due to plant reaction) supports this. Potassium must be replacing Na^+ under the shrub.

Cation-Exchange Capacity

CEC determinations were made for quite a number of samples. The values obtained, however, were very erratic and appeared to be greatly influenced by coal particles in the sample material. Since no useful data was being generated, analysis for CEC was discontinued.

Spoil Texture Analyses

All collected samples were tested for texture. All proved to be clayey; ranging from 42-61 percent clay. The distribution of percentages was random and thus did not appear to play any part in the success or failure of plant establishment. However, in absolute terms, the fact that the material contains such a large proportion of clay is very important to the overall reclamation program and will be discussed later.

Temperature Data

High average temperature is a cause of adversity in bare spoils (Table 2). According to Student's t test, within a slope (either north or south) there is no significant difference between bare or vegetatively covered minimum temperatures. There are,

Table 2. Comparison of air temperatures with bare and vegetatively covered spoil temperatures

Average Temperatures (^{o}C)		
Air	Bare Spoil	Covered Spoil
24.3 a*	37.8 ab	26.3 b
S.E. 1.14	2.11	1.44

*Values followed by same letter are significantly different at the 99.9 percent confidence level however, highly significant differences between bare and covered maximum temperatures on the south and north slopes, $P<0.01$ and $P<0.001$ respectively. Between slopes, there is a significant difference ($P<0.001$) only between covered maximal temperatures.

The statistical differences between bare and covered maxima on either slope only support what would be taken for granted; namely that subsurfaces protected from direct insolation will heat up slower than those not so protected. The lack of differences in minimum temperatures is probably explained by the fact that nights in arid environments are generally cool enough to allow all surface temperatures to return to a common base level. The adjacent north and south slopes were probably gentle enough so that no difference was observed between bare areas. Between shaded points, however, the shading was much more effective on the north slope. Thus cover and slope exposure do, as expected, affect subsurface temperatures by influencing temperature extremes. This influence appears to be very important to the success or failure of germinating seeds. Newly imbibed seeds which are subjected to high temperatures such as the recorded high of 48°C (118.4°F) on the south-bare slope might easily be killed. However, with other conditions essentially equal, seeds under cover on the same slope would experience a mitigated temperature of 42°C (107.6°F) or, on the covered-north slope a temperature of only 35°C (95°F). Average maximal and minimal temperatures are given in Table 3.

Table 3. Minimum-maximum temperature readings (^{o}C)

	South				North			
	Minimum		Maximum		Minimum		Maximum	
Date	Bare	Covered	Bare	Covered	Bare	Covered	Bare	Covered
6/26	9.5	11.5	46.0	44.0	11.0	13.0	39.5	30.0
7/11	15.0	17.0	48.0	42.0	14.0	16.0	45.5	35.0
7/26	13.0	15.0	47.0	45.0	13.0	15.0	49.0	34.0
8/17	12.0	13.5	45.0	37.5	11.0	14.0	45.0	27.5
10/11	0.0	7.0	47.0	34.0	0.0	7.0	46.0	27.0
$\overline{X}$	9.9	12.8a*	46.6	40.5ac	9.8	13.0	45.0b	30.7bc
S.E.	2.63	1.71	0.51	2.07	2.52	1.58	1.54	1.64

*Mean values followed by the same letter are significantly different at the 99 percent or greater confidence level.

Vegetational Analyses

In Figure 3 are illustrated the results of three of the four stratified areas. Species foliar percentage (based on percentage of ground covered) is shown in relation to its position on slopes and in regard to north and south exposures.

The "rolling plains" area was a long, unbroken stretch of spoils which supported very little vegetation. This plain had a number of east-west aligned rolling hills. The study was to detect if the slight differences in exposure would affect vegetational establishment. The results in the "rolling plains" area show a tendency toward higher foliage cover and higher species diversity on the north-facing slopes. The hilltops were, as expected, consistently lower in both respects than either of the two slope exposures studied. Although there are evident differences in the transect results, these differences are not as great as had been visually perceived the previous year. The probable reason for this is the much lower rainfall received at the mine in 1976 than had occurred in 1975. The much drier conditions existing the second year more than likely had a greater effect on the relatively more mesic northern exposures since they had more moisture to lose, thus lowering moisture amounts to the base levels existing on the southern exposures.

The "deep drainages" were formed by steep, abutting spoil banks. The large adjacent unvegetated slopes acted essentially as water-collecting areas during the summer thunderstorm season. This coupled with the added protection from wind and,

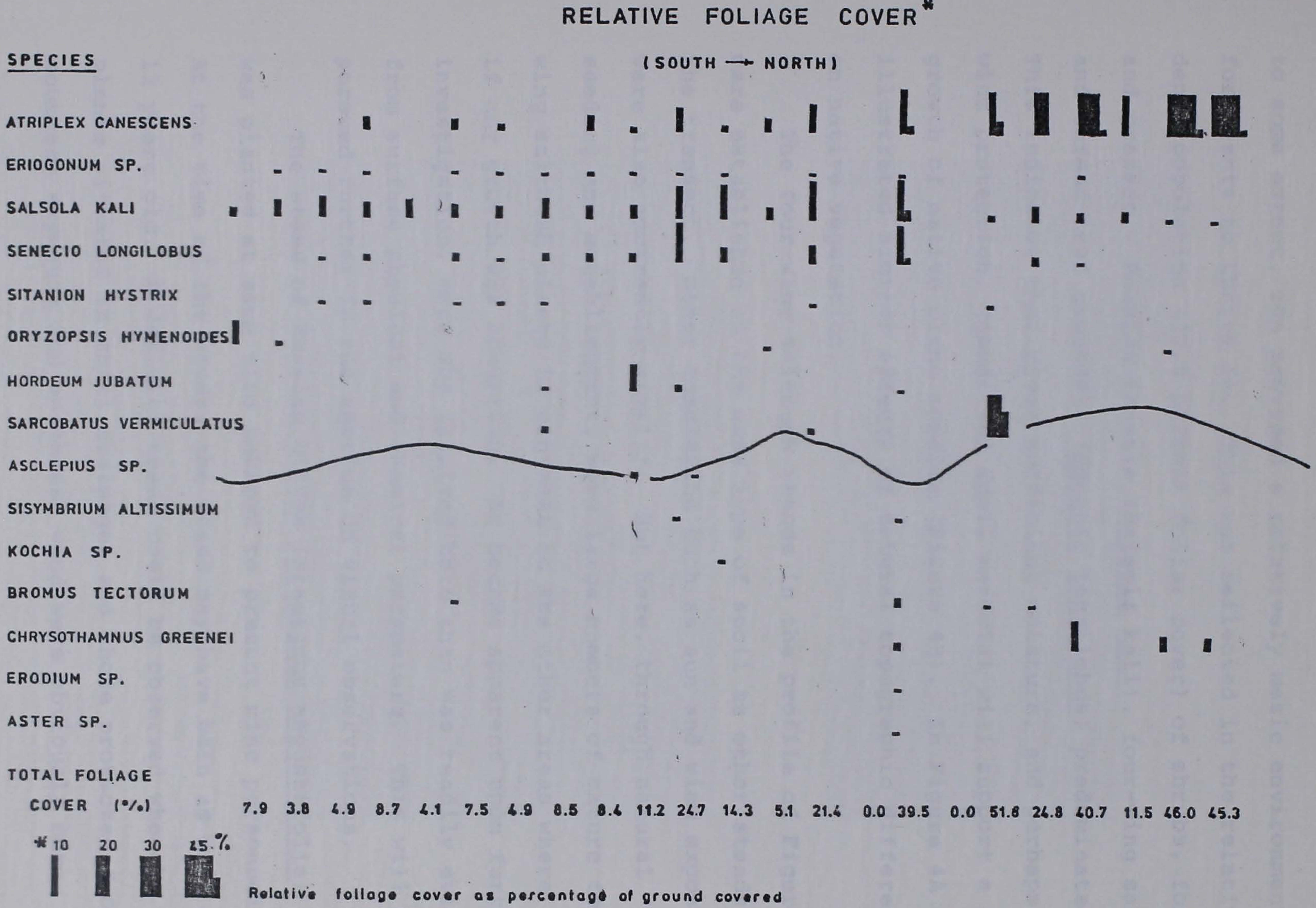
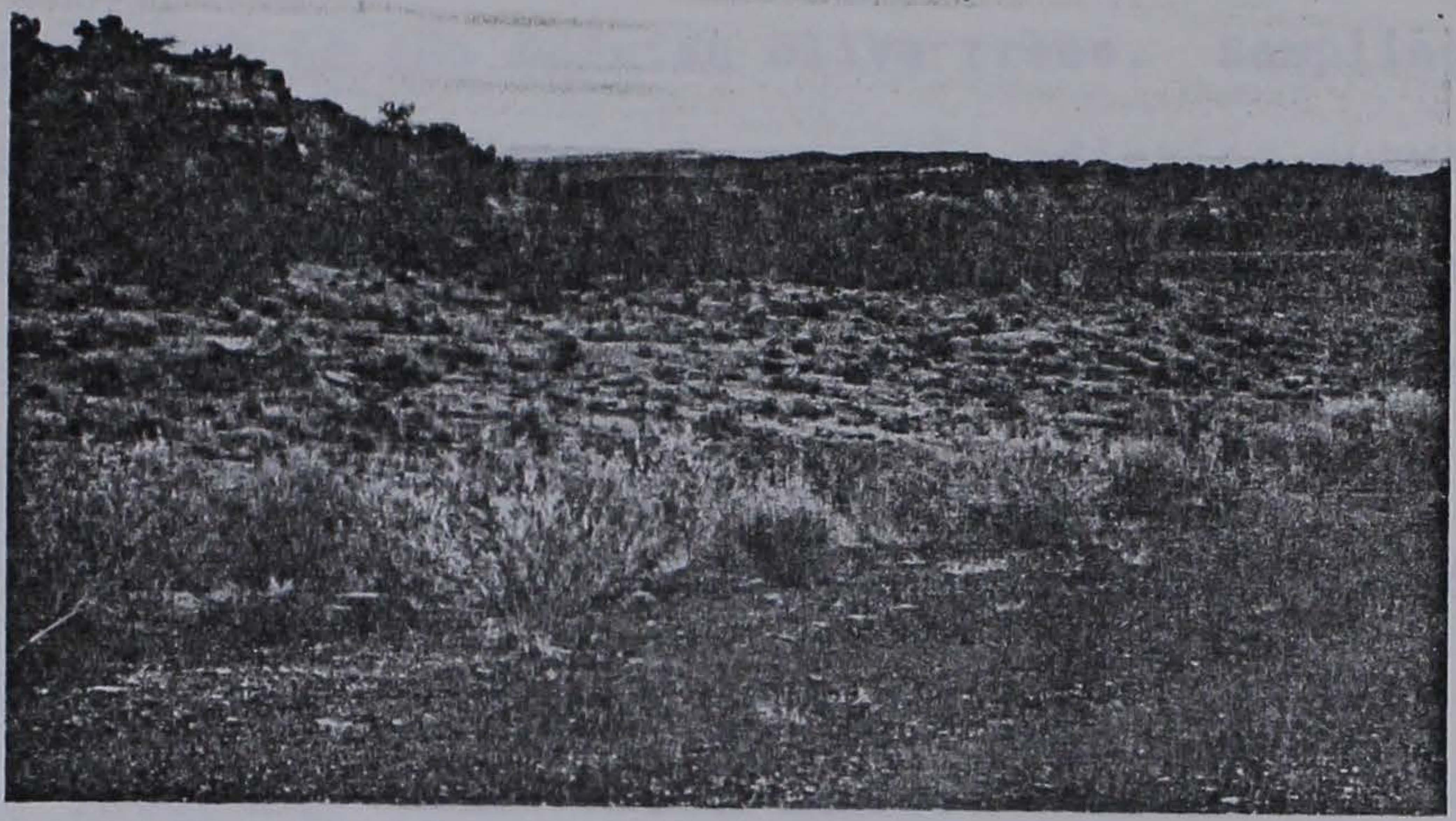


Figure 3. Relationship of total foliage cover, relative foliage cover (percentage of ground occupied by each species), and species composition to relief and slope exposure as determined by quadrats along a line transect.

to some extent, sun provided a relatively mesic environment for plants to thrive in. This was reflected in the relatively dense population (39.5 percent foliar cover) of shrubs, forbs, and grasses. Russian thistle (Salsola kali), four-wing saltbush, and thread-leaf groundsel (Senecio longilobus) predominated. This indicates that given sufficient moisture, and perhaps wind protection, unmodified spoil material will support a dense growth of native plant species (Figure 4B). In Figure 4A is illustrated similar effects of natural topographic differences on native vegetation.

The four-wing saltbush stands in the profile of Figure 3 were established on the same type of spoil as other stands of the transect. Other conditions such as sun and wind exposure were also apparently similar. But here, through natural seeding and establishment, were large numbers of mature four-wing saltbush plants in contrast to the other areas where little if any growth was occurring. As became apparent upon further investigation, more was involved here than was readily evident from surface physical and chemical parameters. This will be pursued further in the section on visual observations.

The stand of Russian olives (Elaeagnus angustifolia) was planted at some time unknown to present mine personnel. At the time of the study, the stand may have been as much as 12 years old. A definite trend could be observed whereby plants situated in small drainages and those protected from the southern exposure and southwest wind were obviously more



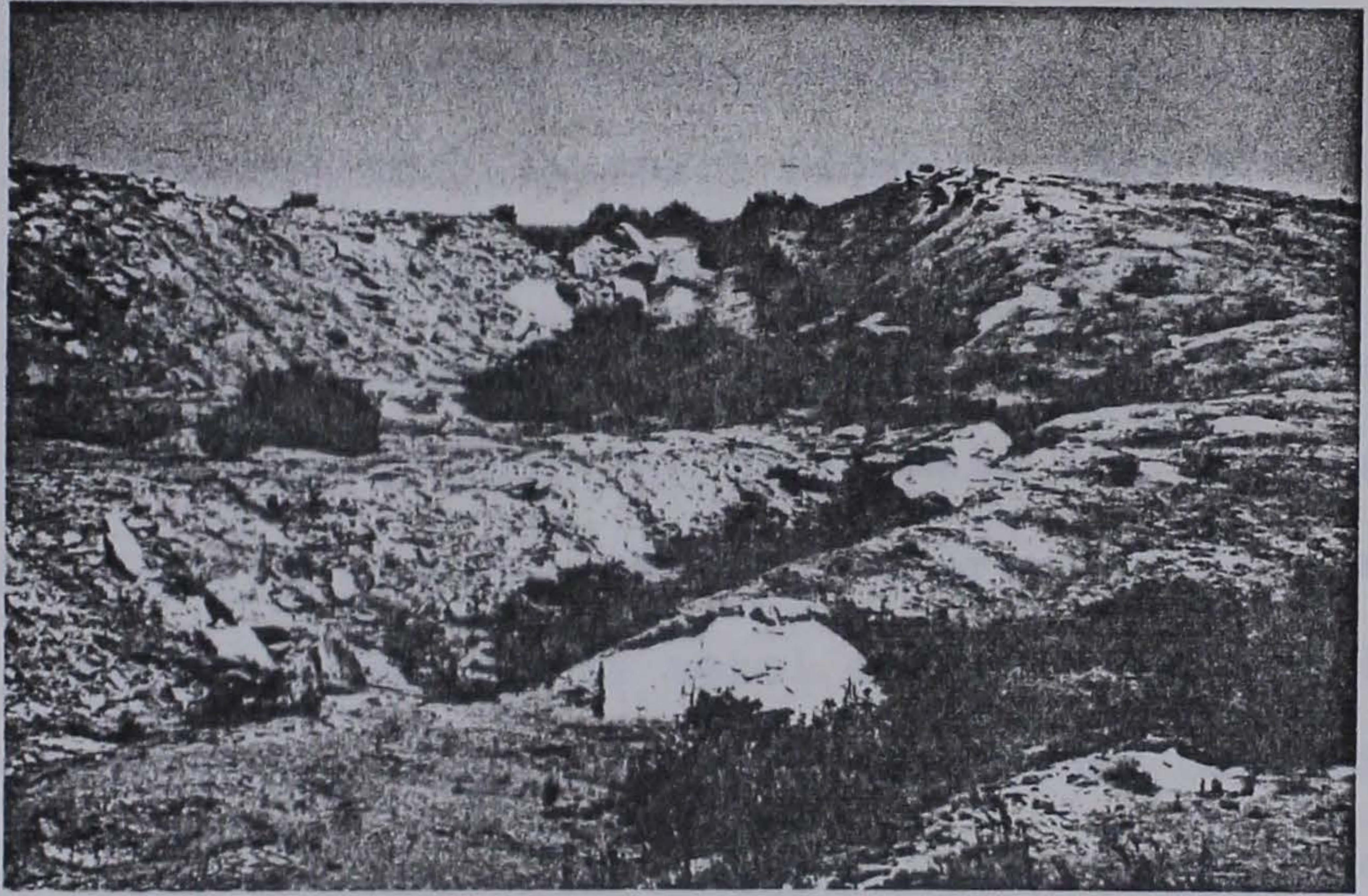
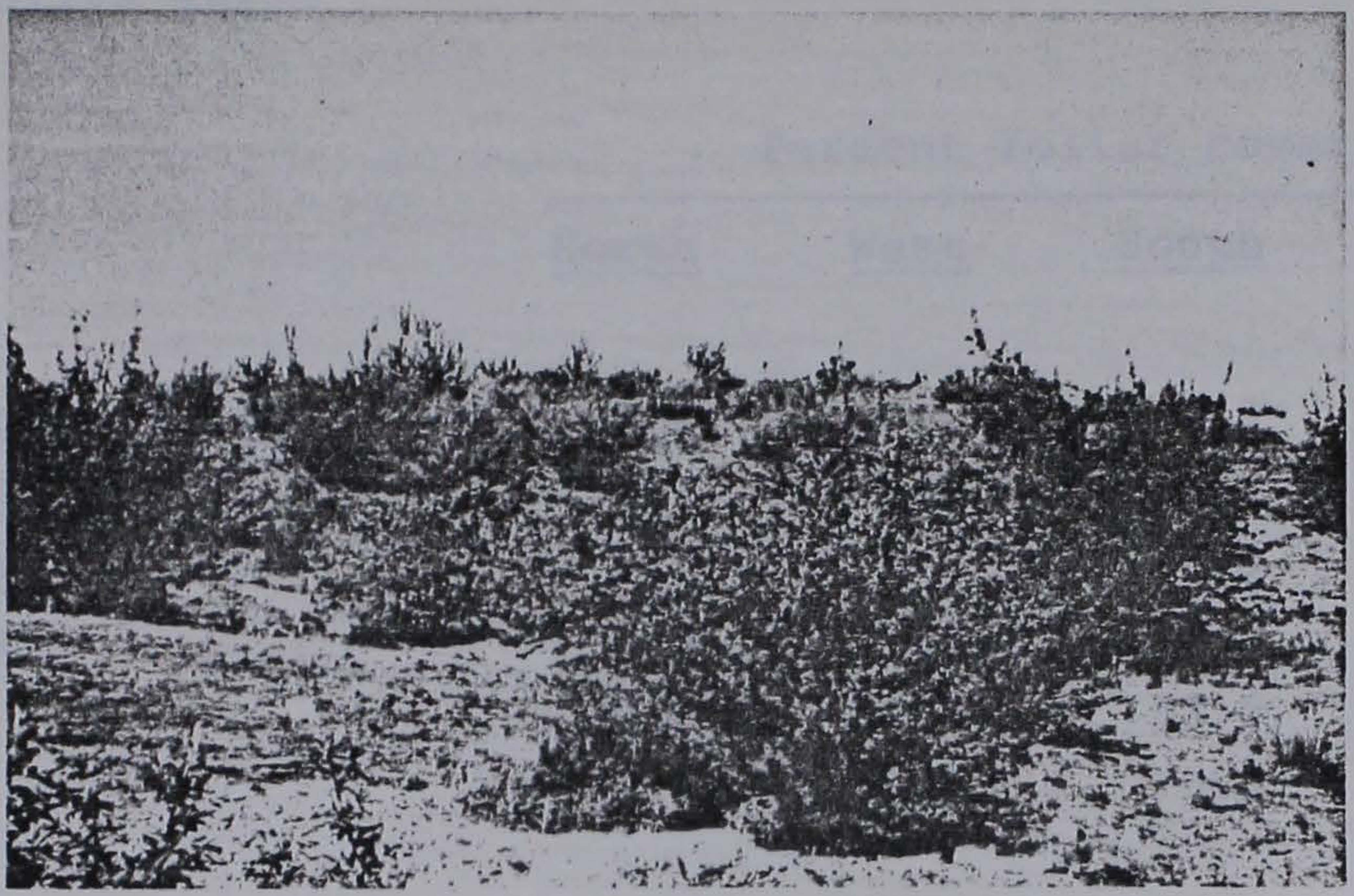


Figure 4A. Natural irregular topography illustrating the growth of shrubs and pinyon-juniper on steeper slopes and rock outcrops and grass and sagebrush on gentler slopes and finer soils.

4B. Natural plant succession on irregular "deep drainage" spoil topography showing effect of relief and rocky texture on establishment of four-wing saltbush and cheatgrass.

vigorous (Figure 5A, B). The sampling, however, attempted only to describe the accompanying ground cover as a function of the presence of the Russian olive trees. Sampling included four 2-meter line intercept transects radiating outward in the four cardinal compass directions from the center of each tree. The results not only show how dramatically the presence of the trees hastened natural plant establishment, but also how the exposures around the tree affect the success of invading plant species. The north and east sides of the trees were generally the more favorable sites while the south and west sides, with their exposure to the summer's extreme insolation and wind, supported much less vegetation (Table 4). In cases where there was relatively good cover on the latter two sides, there were mitigating factors such as small rises on that side which broke up the wind or shaded the site. A factor that limited plant growth on all sides was the occasionally high accumulation of Russian thistle litter. An additional set of line intercept transects was run from the stump of a previous Russian olive tree. A considerably higher total foliar cover was found here than under existing trees although other conditions appeared to be similar. One species was present here which had not been observed previously on mined spoil material, either in this study, or by Wagner (1975). It was a species of *Astragalus*. From the vigorous growth occurring here, it appeared that the initial protection probably given by the now dead tree was enough to allow some species to germinate and establish themselves before that protection was removed. Or,



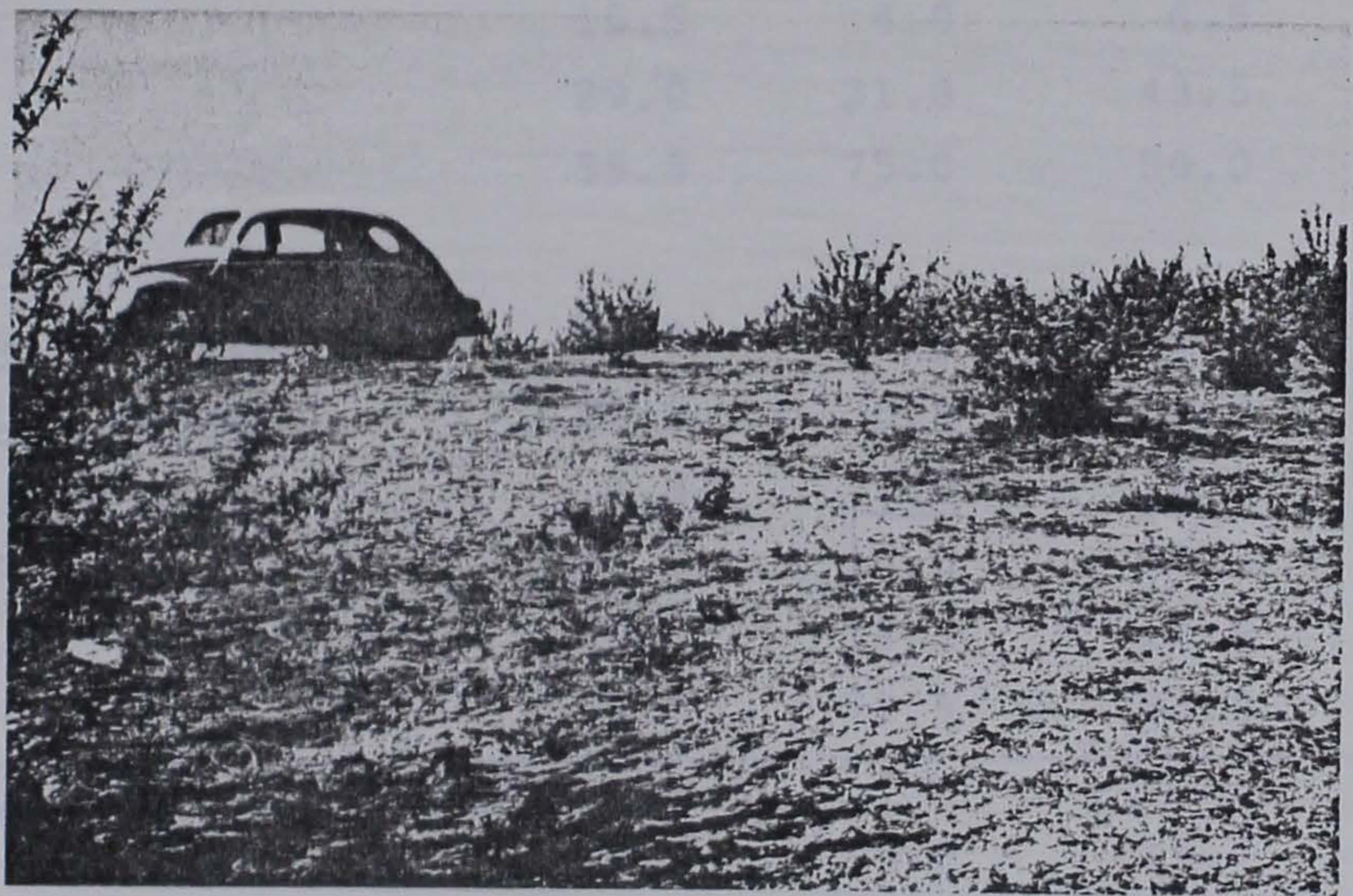


Figure 5A. Planted Russian olive stand with vigorous growth in response to wind protection and irregular ground surface.

5B. Adjacent stand of Russian olive with relatively stunted growth in a location exposed to wind and a smoother surface.

Table 4. Line intercept of understory vegetation in Russian olive stand

Species	Percent foliar cover			
	North	West	South	East
Site A.				
Sitanion hystrix	0.0	5.0	5.5	9.0
Salsola kali	0.0	0.0	0.0	27.5
Lactuca sp.	0.0	0.0	0.5	0.0
Total cover	0.0	5.0	6.0	36.5
Litter	20.0	20.0	23.5	13.0
Bare	80.0	75.0	70.5	50.5
Site B.				
Sitanion hystrix	11.0	4.0	6.5	12.5
Salsola kali	4.5	0.0	0.0	0.0
Total cover	15.5	4.0	6.5	12.5
Litter	29.0	21.0	43.5	38.0
Bare	55.5	75.0	50.0	49.5
Site C.				
Sitanion hystrix	13.5	15.0	22.5	17.5
Marrubium vulgare	12.5	0.0	0.0	0.0
Bromus tectorum	2.5	0.0	0.0	0.0
Total cover	28.5	15.0	22.5	17.5
Litter	20.0	12.5	22.5	22.5
Bare	51.5	72.5	55.0	60.0
Average foliar cover (A,B,C)	14.7	8.0	11.7	22.2
Site D. Vegetation under dead Russian olive				
Sitanion hystrix	24.0	0.0	5.0	0.0
Salsola kali	1.0	0.0	0.0	21.5
Astragalus sp.	7.5	5.0	4.0	2.5
Marrubium vulgare	0.0	0.0	0.0	13.5
Atriplex canescens	0.0	0.0	0.0	4.5
Total cover	32.5	5.0	9.0	42.0
Litter	19.0	10.0	26.0	42.0
Bare	48.5	88.0	65.0	16.0

the spoil conditions had been changed by the presence of the tree in regard to organic matter content, salt concentration, moisture relations, or other factors which later allowed establishment without the benefit of the tree's protection. One apparent benefit in the tree's absence was the lack of the thick accumulations of Russian thistle litter that totally precluded at times any plant establishment under the Russian olive trees.

While a large number of plant species were found on the spoil areas, only a few predominated. These included: four-wing saltbush, rubber rabbitbrush (*Chrysothamus nauseosus*), squirrel-tail (*Sitanion hystrix*), cheat-grass (*Bromus tectorum*), and fox-tail barley (*Hordeum jubatum*). Other species such as greasewood (*Sarcobatus vermiculatus*) and *Atriplex saccaria* were only locally abundant.

Litter Examination

Litter samples were collected from underneath shrubs in order to determine whether established plants on the spoil banks were acting as traps of both soil and seeds blown in from peripheral unmined areas. From the samples studied, it appears that no perceptible amounts of native soil particles are collecting under plants in the study area. Of the seeds found in the samples, only one species, those of stickseed (*Lappula* sp.), could be attributed directly to a source outside of the mined spoils. Large numbers of stickseed plants were found growing in the nearby pinyon-juniper community. Other seeds found in abundance which could just as easily have come from on-spoil plants were: Russian thistle, cheatgrass, Atriplex saccaria, greasewood, four-wing saltbush, and fox-tail barley or squirrel-tail. In addition to the above, other materials found in the litter could also enhance conditions on and in the spoils. These were to a large extent, wind-blown sandy spoil material and rabbit pellets, and to a lesser extent, insect parts. The sandy spoil material was very often deposited on the lee-ward side of plants where it was mixed with other material such as rocks, Russian thistle litter, etc. Rabbit pellets were at times in great abundance under shrub canopies, especially in areas close to the unmined periphery. The effect of established plants as traps of seeds and soil from the unmined periphery appears to be limited. The total effect of plants as traps of seed and spoil particles appears significant (Figure 6).

Visual Observations

Effectiveness of seasonal precipitation

Considering the limited amount of precipitation received at McKinley Mine, the efficiency of absorption, retention, and utilization of that precipitation is most important in any revegetation scheme, either natural or man-induced. The effectiveness of summer precipitation, occurring as it does in the form of short duration - high intensity thunderstorms, is generally limited. The clayey spoil material, with its montmorillonite element, seals the surface quickly upon wetting. The result is massive runoff into drainages and sumps. The

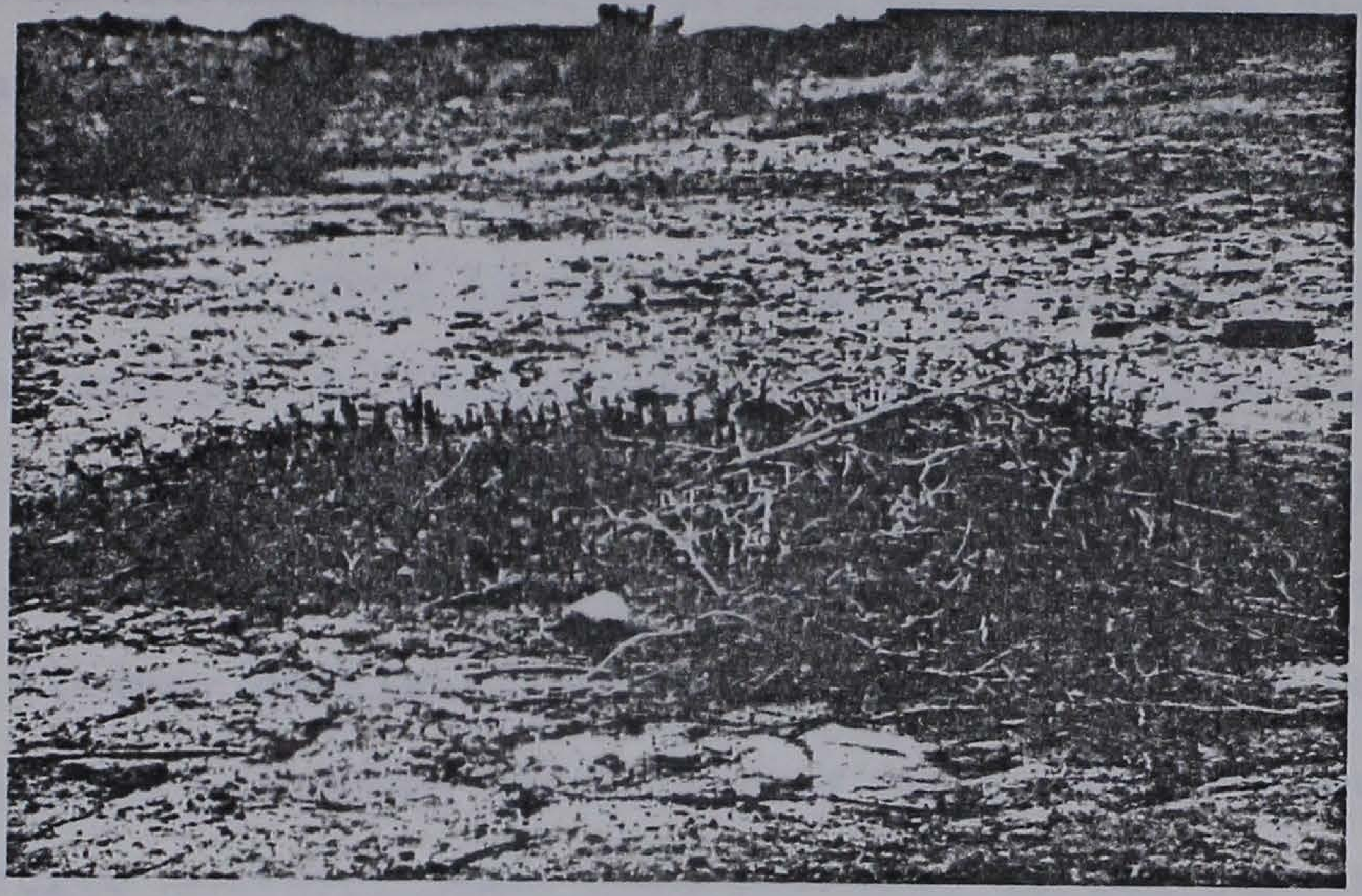


Figure 6. Example of amount of organic matter accumulated under a naturally established greasewood plant from its own litter plus trapping of wind blown organic material. Greasewood plant was removed to expose the litter.

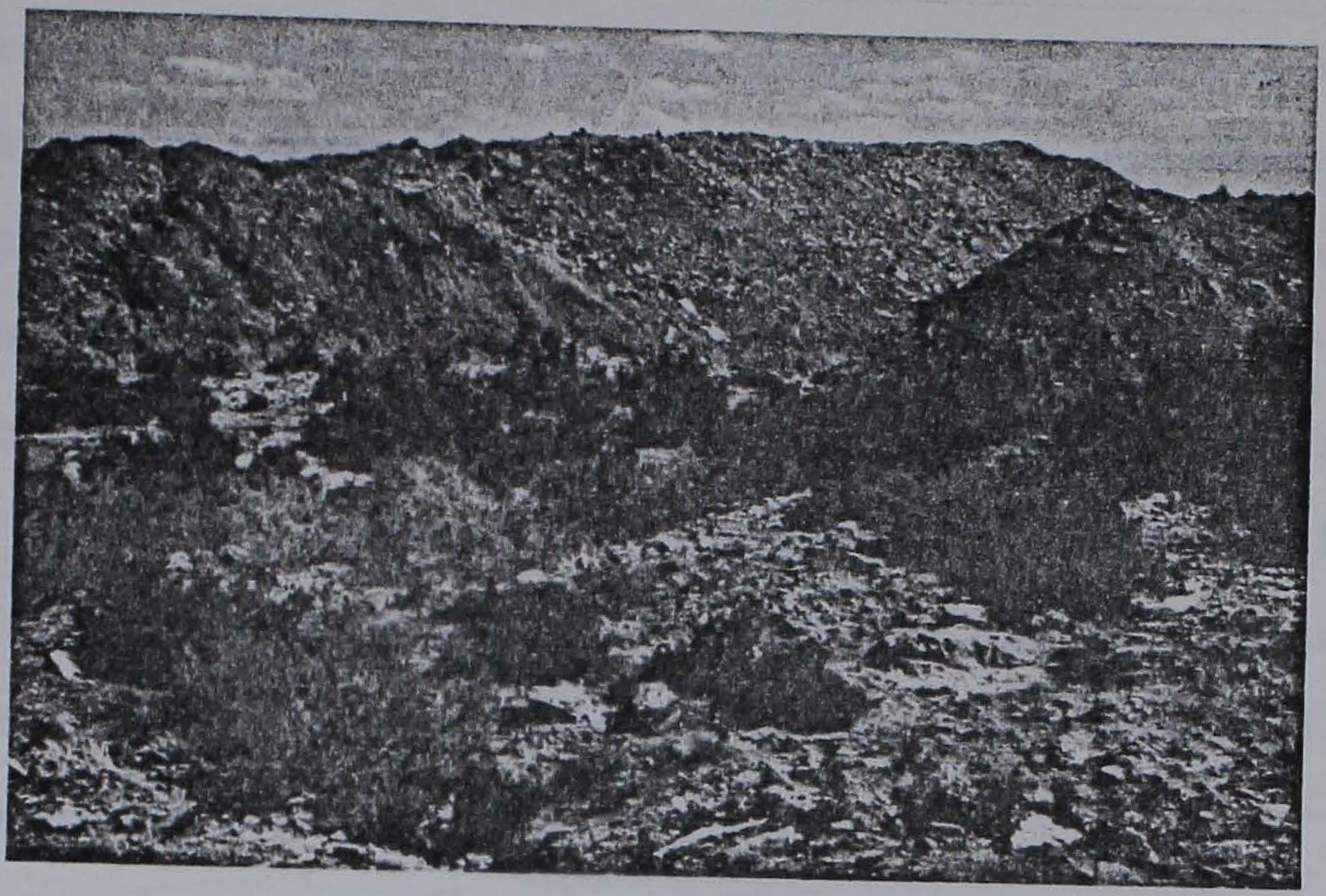
drainages are usually the sole beneficiaries as is evidenced by the relatively luxuriant growth occurring in them. The sump areas generally receive the largest amount of the runoff, along with high concentrations of suspended clays and dissolved salts. Consequently, these sites rarely supported more than a few scattered squirrel-tail and an occasional greasewood. As mentioned earlier, it was observed that summer precipitation was effectively funnelled to root systems of four-wing saltbush via stemflow. This is an important effect of established plants on the spoils, in that stemflow traps otherwise lost moisture both for the established plants and for the understory seedlings.

Winter precipitation, generally in the form of snow, occurs in a slower, gentler fashion. This, in addition to the slow melting of the snow, results in a much greater amount of effective moisture than that received in the summer. An important part of the winter moisture, which percolates down through the spoil material, was often-times retained through the spring drought at depths of approximately 25 cm and greater. This was especially true on sites where large numbers of surface and sub-surface boulders existed, and as a result, these sites invariably supported the greatest shrub densities of any naturally populated spoils on the mine.

Two areas in particular were of interest. One was the dense four-wing saltbush stand through which transects were run, the results of which are shown in Figure 3. Here, conditions appeared to be similar to the surrounding, essentially bare, spoil banks. However in contrast, under the dense saltbush it was often impossible to collect below 30 cm any spoil samples that contained soil-sized particles. The subsurface was strewn with rocks. The second site was a mature stand of greasewood. Here, boulders were strewn about on the surface forming a rough but aesthetically acceptable surface which also is of advantage to plant growth as evidenced by the vigorous growth of vegetation (Figure 7A, B). The scattered boulders, coupled with a relatively high water table, formed an environment which supported not only greasewood but grasses, forbs, and even a healthy 15-foot cottonwood tree (*Populus fremontii*). The rocks and small gullies in this area not only acted to trap and retain moisture but also broke up the otherwise almost incessant, dry southwesterly winds in the summer.

Effect of slope exposure

Direction of exposure and insolation are both by-products, in a sense, of physiography. Opposing slopes are often subjected to distinctly different microclimates. Differences in temperature and available moisture result in marked vegetational differences (Humphrey 1962). Such differences were frequently found on the spoil banks. In one area, where the annual *Atriplex saccaria* was abundant, north-facing slopes supported a dense cover of the weed after a moist spring. The abutting south-facing slope was essentially bare. The importance of winter precipitation is enhanced by northerly slope exposures. Here, winter snows can easily last into the spring. While south-facing slopes are beginning to warm up and promote seed germination, seeds and dormant plants on north-facing slopes



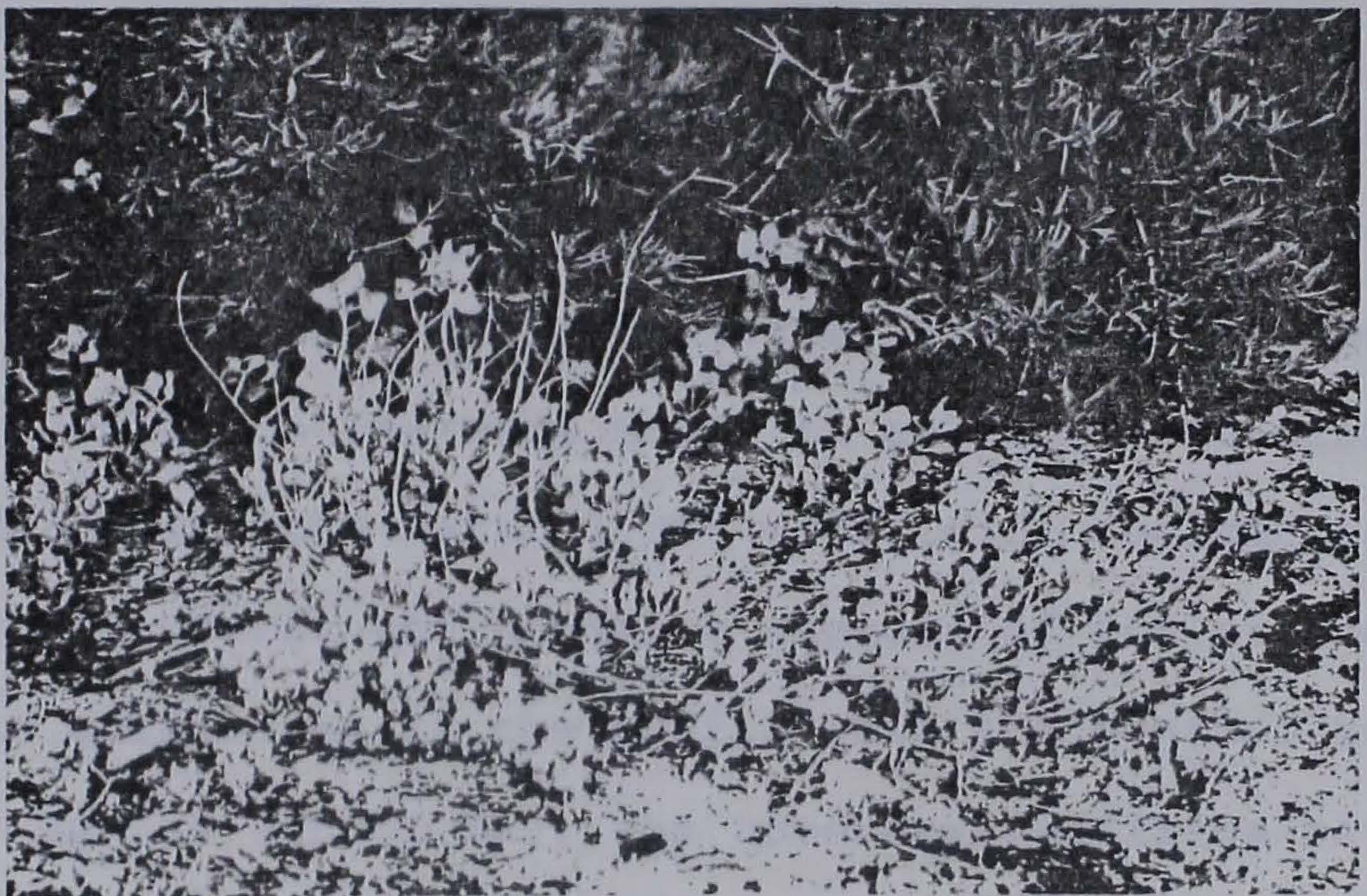


Figure 7A. Vigorous greasewood-four-wing saltbush stand developed on area of irregular topography with boulder-strewn surface.

7B. Detail of Atriplex saccaria growing adjacent to larger greasewood in the area of 7A.

are still either covered with snow or retarded by the colder temperatures there. As a consequence, the early germinating plants on the south-facing slopes soon run out of moisture as the spring drought procedes. These plants rarely survive long enough to take advantage of the summer rains unless they are protected by physiographic or other features. On the other hand, the later germinating plants of the north-facing slopes start out with more available moisture and spend less time in the susceptible seedling stage before the advent of summer thundershowers.

A small study was conducted in the early spring of 1976 in which a number of different plant species were seeded in fenced-off plots on north- and south-facing slopes. Unfortunately, the winter of 1976 was so dry that no germination ever occurred.

The role of Russian thistle on mine spoils

The fact that Russian thistle is by far the most numerous plant species on the mine makes it an important element to be considered in both natural and artificial reclamation. Considering first the negative aspects of its presence, Russian thistle germinates in the spring when the weather is still cool. By the end of May, the numerous seedlings have taken over almost every favorable site. If moisture conditions continue to be favorable, a rank growth occurs. The plants then usually out-compete other, less vigorous plant species for both moisture and space. After the growing season, when the Russian thistle breaks loose from its root, it tumbles along in the wind, disseminates its ripened seeds, and often accumulates in great piles under trees and shrubs (Figure 8). These accumulations often preclude any understory growth. If a dry winter and spring are experienced, fewer Russian thistles will germinate, and those that do will be stunted. When the summer precipitation finally arrives, the plants have a renewal of vegetative growth but don't attain a normal vigor, thus allowing other species a chance to compete with them. This fact could be put to use on a reclamation site where irrigation is used. A positive side to the near ubiquity of Russian thistle is the large number of seedlings present in late spring and early summer. As intraspecies competition for space progresses, large numbers of the seedlings die leaving their already long (> 30 cm) taproots and succulent leaves to decompose in a spoil material deficient in organic matter. Upon digging in these sites, one can easily see the impact of the roots, as they bind the spoil particles together and provide a fresh nutrient source for the spoil microbial population. The spoils at these sites already have the feel and smell of a soil rather than the apparent total lifelessness of raw spoil material. The soil-building process is definitely assisted by the presence of Russian thistle. The above ecological reaction is a favorable attribute toward soil development and plant succession of a species usually considered a noxious pest.

Compaction of spoil material

Another possible factor in the establishment of plants on the spoil banks is the degree of compaction of the spoil material. Much of the shaley-clayey material was extremely loose to

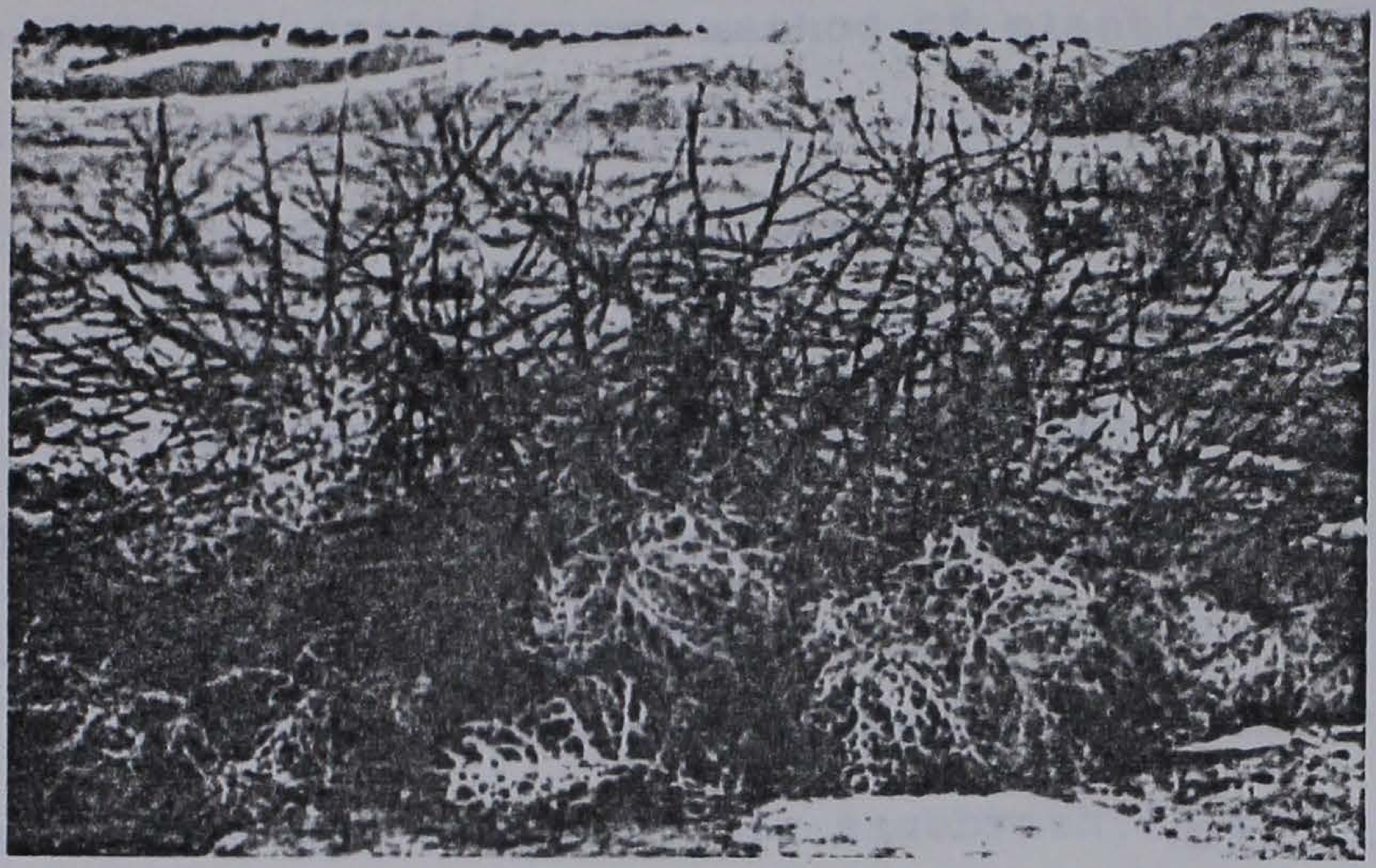


Figure 8. Accumulation of wind-blown Russian thistle on windward side of Russian olive.

depths of 20 cm and greater. These areas supported very little vegetation. It would appear that this lack of compaction might at least partly be responsible for the lack of plant establishment, since an uncompacted seedbed is often a poor seedbed. In general compaction of soil beneath the seed, pressing the seed into the compacted surface, and covering it with uncompacted soil appear to be the most satisfactory method of planting. The results are likely to be related to the period for which the water supply at the position of the seeds is optimal (Malcolm 1972). The compaction at and below the level of the planting would tend to slow down the moisture infiltration and retain a larger amount of it.

Lack of big sagebrush invasion

A question asked during the study was: why was there no invasion onto the spoils by big sagebrush (*Artemisia tridentata*)? Much of the unmined periphery was populated by big sagebrush, so lack of seed source didn't appear to be the problem. A greenhouse pot study revealed that good germination (88%) was possible for big sagebrush seeds when they were placed on the surface of spoil material. The seedlings were, however, quite sensitive to drying, their recovery being quite poor. According to Goodwin (1956), water is a more important disseminating agent for big sagebrush than is wind. At McKinley mine, the seed source is invariably at elevations below the spoil banks, thus precluding water as a transport medium onto the spoil banks. Daubenmire (1975) found that contact with free water is essential for good germination, and temperatures must be cool, at least at night. Spoil water infiltration and retention characteristics may be such as not to provide proper moisture conditions for germination when temperatures are optimal. One big sagebrush plant was eventually found on the old spoils. It was located in a shallow, protected drainage and appeared quite vigorous, despite evidence of some grazing upon it. The seed may have been transported there via an animal. Although only one plant was found, its presence provides evidence that, given a seed supply, spoil material could very likely support a big sagebrush population.

Success of *Atriplex saccaria* on spoils

Atriplex saccaria, an annual forb, is a typical indicator of eroded shales. It can tolerate soil salt contents of 2 percent and greater (Hall and Clements 1923). *Atriplex saccaria* was important at a number of sites. It was often found thriving in the severest conditions in terms of spoil salt and clay content. Where large populations occurred, much litter had accumulated over the year and was found to be in varying states of decomposition. Although the high salt content of the foliage renders the plant largely unpalatable for livestock (Hall and Clements 1923) and may result in salt accumulations at the spoil surface, it was thought that *A. saccaria* might be of some value in the revegetation of sites too harsh for other plant species. Some germination experiments were performed in the laboratory to determine some of the plant's germination requirements. Initial germination trials with unwashed, unstratified seeds on blotter paper resulted only in amber-colored exudates appearing on the fruit bracts. Beadle (1952) encountered this same phenomenon in dealing with other Atriplex species. He concluded that the bracts contained large concentrations of chloride ions, resulting in high osmotic pressures and retarded germination. Stratification of the seeds for 45 days at 2° C was more than sufficient to obtain good germination results. In fact, some germination had already begun during stratification. Seeds collected on the ground in May had mostly lost their bracts, probably due to a combination of mechanical abrasion from the seeds being blown along the ground and from their decomposition during the previous winter.

CONCLUSIONS

Causative Factors

Of all the factors considered, topography and the presence of rocks on and below the surface appeared to be the most important features in promoting vigorous initial plant establishment on the spoil banks. An irregular topography creates numerous, scattered, and relatively mesic habitats in an otherwise xeric environment. In the hot and dry periods of the year, the irregularities break up and divert the desiccating winds and shade out the intense summer insolation. Summer rains, which usually result in very little moisture infiltration on graded spoils, get trapped and concentrated by the numerous water harvest areas in a broken topography. The moisture is then held long enough to allow infiltration to occur. Wind-blown snow in the winter months is effectively stopped and deposited on the leeward side of surface irregularities. This provides much needed moisture that might otherwise be lost to plant utilization.

Surface and subsurface rocks essentially mimic an irregular topography. They also act to break up wind and to shade the spoil surface. Summer rainfall, which is concentrated on the rock surfaces, flows onto the spoils and becomes trapped beneath the surface and subsurface rocks. Here, it is protected from evaporation and held as a reservoir for future use. Hence, this action tends to mitigate the poor infiltration properties of the clayey spoil material. A rocky surface also acts as a trap for blowing snow and sand particles. Again, the snow is concentrated and results in increased available moisture. The wind-blown sand forms small dunes on the leeward side of the rocks. These also form favorable microsites where moisture relations are improved.

North- and east-facing slopes also provide a more favorable environment for plant growth. Summer conditions are less severe on these slopes than on the other slopes. Snow melts more slowly resulting in the infiltration of a greater percentage of the total precipitation. The slopes stay cooler longer, which retards both evaporation and seed germination. The result of this is a reduction both in duration and severity of the spring drought which leads to a denser and more vigorous stand of vegetation able to take advantage of the summer rains.

Litter accumulation around topographic features serves to reduce surface temperature extremes, improve moisture relations, and provide a cover for light-sensitive seeds such as those of cheatgrass (Daubenmire 1975).

Salinity levels of McKinley Mine spoil material do not appear to be a limiting factor in plant growth. Both laboratory analyses and the success of many naturally established species support this. In fact, greenhouse pot studies have shown that seedlings emerged as well (or better) in spoil as in topsoil (Aldon, et al. 1975). One possible exception would be in the sump areas, where runoff-carried salts would accumulate. However, the heavy clays there would be just as big a problem.

Reactions

Shrub and tree canopies create micro-environments similar to those provided by the rocks and topographic features described above. They provide shading which translates into reduced evaporation and moderation of temperature. They serve to trap wind-blown litter and seeds and also contribute their own litter and seeds to the surface. Their roots penetrate the spoil, improving moisture and air infiltration, adding organic matter directly to the subsurface, and thereby stimulating microbial activity in the spoil. This benefits the plant and accelerates the soil-building process. Forbs and grasses also contribute to this process, providing every year much needed organic matter to the spoils.

Established plants do not appear to be important as traps for wind-transported seeds and soil originating from areas peripheral to the mine spoils. They do, however, effectively trap and retain wind-blown sandy spoil material, litter, and seeds originating on the spoils themselves. One probable reason for the lack of wind-blown seeds from the undisturbed periphery is the fact that the dominant plant species in those areas are also climax species (_Pinus edulis_, _Juniperus monosperma_, and _Artemisia tridentata_). As such, they would not have the highly efficient transport mechanisms that are so important to the primary invading species. The understory vegetation in these areas, though disturbed by severe overgrazing, probably does not act as a seed source because of the very fact that it is so severely overgrazed.

The establishment of the shrub, four-wing saltbush, has an important effect on the sodium and potassium concentrations of the spoil within its sphere of influence. Apparently, through the improved moisture conditions under the plant, sodium is being leached downward, thereby creating spoil conditions more favorable for the less salt-resistant species to invade the spoil banks. Potassium, on the other hand, is accumulating under the shrub canopies despite the solubility of potassium salts. This concentrating effect may be due to properties of the montmorillonite clay fraction in the spoils and the way potassium ions react with it. This buildup may produce long-range benefits both as a source of the nutrient for plant use and also as a possible agent in the prevention of swelling and sealing off of the spoil material.

RECOMMENDATIONS

Consideration of the results of this study leads to a number of recommendations which should increase the efficiency of strip-mine reclamation programs, both at McKinley Mine and other mines with similar environmental challenges.

The policy of forming spoil banks into long, unbroken grades should be stopped. Alternately, more numerous and shorter slopes should be produced. In conjunction with this, large and small rocks should be added to the spoil surface and subsurface, especially on south- and west-facing slopes. A program to effect this could be managed much as are present programs to add topsoil to the surface. Seeding methods would have to be modified, utilizing broadcast seeding more than is now being done. Smaller tractors and other equipment would probably have to be used in these situations.

If irrigation is used, spoils not formed as above should be irrigated in the spring to promote heavy germination of cool-season weeds such as Russian thistle. After a period of growth, the water should be withheld to allow drought and competition to kill the weeds. Before the summer rains, the vegetative growth should be plowed under. The plants could be used as a green manure mulch if allowed to grow longer before plowing under and if growth would not be unmanageably thick. Subsequently, warm-season species should be planted to take advantage of the summer precipitation.

In addition to the use of spring weeds as green manure, the use of fall-planted grasses such as winter rye should be considered as a source of organic matter and nutrients. Fall plantings should be well enough established in the spring to compete with cool-season weeds and could be plowed under prior to the planting of warm-season species following the advent of the rainy season.

Climatically adapted species of shrubs and trees such as four-wing saltbush, Russian olive, pinyon, and juniper should be included in any reclamation attempt in order to provide cover for subsequent plant establishment and wildlife. Many shrub species can most effectively be planted via seeding, while the above-mentioned tree species will do best if transplanted. The pinyon and juniper should be planted amongst the rocky surfaces mentioned earlier, as those are more nearly their natural habitats.

Surface manipulations following the recommendations of Hodder (1973) should be considered where the formation of rocky surfaces is impractical.

On sites where germination and establishment are poor, the need for proper compaction of the seedbed should be considered.

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APPENDIX

Analytical Procedures

1. Spoil texture

Spoil texture analyses were conducted according to the hydrometer method described by Bouyoucos (1936).

2. Electrical conductivity and pH

Saturated paste extracts and subsequent electrical conductivity and pH values were obtained following methods outlined by the U.S. Salinity Laboratory (USDA 1954). Ec values were expressed as millimhos per cm (mmhos/cm).

3. Elemental analyses

Spoil extracts used in elemental analyses and cation-exchange capacity determinations were obtained by methods slightly modified from those described by Chapman and Pratt (1961). Five gram samples (air-dry) were subjected to seven consecutive washings in a 1.0 N, pH 6.0 solution of NH_4OAc. After each washing, the solution was centrifuged for 15 minutes or until the supernatant liquid was clear. The supernatant was then decanted and the pellet redissolved and shaken another five minutes. All washings per sample were added together. These were analyzed for calcium, magnesium, sodium, and potassium with a Perkin-Elmer Model 306 atomic absorption spectrophotometer. Readings were transformed from percentage values to milliequivalents per 100 grams of spoil.

4. Percentage moisture

Samples were oven-dried at 105° C until constant weights were obtained. Field moisture percentages were divided by saturated paste moisture percentages in order to provide a common index of available moisture. Since the purpose of the study was the comparison of different zones, absolute moisture availability values were not considered necessary.